LEVEL II (12)

RADC-TR-81-8
Phase Report
March 1981

AD A098104

ELECTROMAGNETIC SIMULATION OF MISSILE EXHAUST PLUMES, CONSTRUCTION & TESTING OF A PHYSICAL PLUME SIMULATOR & THE PREDICTED RESULTS OF A THEORETICAL "THIN-WIRE" ROCKET/PLUME MODEL

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: RADC-TR-81-8
2. GOVT ACCESSION NO.: AD-A098104
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): ELECTROMAGNETIC SIMULATION OF MISSILE EXHAUST PLUMES, CONSTRUCTION & TESTING OF A PHYSICAL PLUME SIMULATOR & THE PREDICTED RESULTS OF A THEORETICAL "THIN-WIRE" ROCKET/PLUME MODEL
5. TYPE OF REPORT & PERIOD COVERED: Phase Report
6. PERFORMING ORG. REPORT NUMBER: N/A
7. AUTHOR(s): G. S. Smith, J. D. Nordgard, W. A. Holm, H. L. Bassett
8. CONTRACT OR GRANT NUMBER(s): F30602-78-C-0120
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Georgia Institute of Technology, Atlanta GA 30332
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 64747F, 20640303PF
11. CONTROLLING OFFICE NAME AND ADDRESS: Rome Air Development Center (RBCA), Griffiss AFB NY 13441
12. REPORT DATE: Mar[redacted]81
13. NUMBER OF PAGES: 30
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Same
15. SECURITY CLASS. (of this report): UNCLASSIFIED
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report): Same
18. SUPPLEMENTARY NOTES: RADC Project Engineer: John H. Edwards, Jr. (RBCA)
19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
   - Simulation
   - EM Waves
   - Plasma Effects
   - Electromagnetic Compatibility
20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

A full scale simulator of a typical low attitude missile plume was constructed. Carbon loaded foam was used in the model to simulate the electrical conductivity of the ionized exhaust gases expelled from the solid propellant motor. Theoretical computations made with the Low Altitude Plume Program (LAPP) were used to determine the distribution of conductivity in the simulator.

A full size missile with the plume simulator attached was tested in an

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anechoic chamber. The missile was exposed to electromagnetic radiation and the voltage at an internal test point in the circuitry was measured to determine the amount of energy that was coupled through the apertures in the missile. Azimuthal interference patterns were constructed by varying the angle of the incident radiation. The experimental patterns are in fair agreement with those computed from a simple theoretical electromagnetic analysis.

I. INTRODUCTION

The exhaust plume of a missile is an ionized gas or plasma and its presence can alter the interaction of an electromagnetic wave with the missile. In certain instances, therefore, the plume should be present when electromagnetic measurements are made on the missile, such as a measurement of the energy coupled through an aperture in the skin of the rocket. Ideally, the measurements should be made with the actual exhaust plume; but, due to the expense associated with missile firings and the difficulties associated with the logistics and instrumentation, this is often impractical. For example, measurements using precise electromagnetic exposures are often performed in a calibrated anechoic chamber; however, due to the flammability of absorber materials and size limitations, it is impossible to fire a missile in most anechoic chambers.

An alternative to using the actual plume is to use a model or simulator for the plume. There are two methods that can be used to determine the parameters to be used in constructing the model. If measurements of the electrical constitutive parameters and their spatial distributions (or equivalent quantities) are available or can be made in the actual plume, these can be used in the construction of the model. Alternatively, a thermochemical analysis performed on a computer can be used to estimate the electrical constitutive parameters and their distributions in the plume. The difficulties and expense associated with making measurements on the plume during its short burn time make the latter approach more attractive.

For the plume model presented here, i.e., that for a typical surface to air tactical missile at an altitude of 5000 ft., the LAPP (Low Altitude Plume Program) code was used to generate the electrical constitutive parameters (effective permittivity ε_e, and effective conductivity σ_e) as a function of the radial, ρ, and axial, z, positions in the rotationally symmetric (about z axis) exhaust plume [1]. At all positions in the plume, the effective relative permittivity is approximately $\varepsilon_{er} = 1.0$ at the frequencies considered. The effective conductivity σ_e predicted by the code is shown in Figure 1 as a function of the normalized axial and radial positions in the plume, i.e., s/ℓ_m, where s is the axial distance from the exit plane of the motor and ℓ_m is the length of the missile, and ρ/a, where ρ is the radial position from the axis of the plume and a is the radius of the missile. Note that in Figure 1 the scale for the radial axis (ρ/a) is expanded by about a factor of 12 over that for the longitudinal axis.

II. SELECTION OF MODEL MATERIALS

A. Initial Attempt to Formulate the Model Materials

The constitutive parameters produced by the computer indicate that the effective relative permittivity of the plume is very nearly one, $\varepsilon_{er} = 1.0$, at the frequencies of interest and that the maximum effective electrical conductivity is $\sigma_e = 0.25$ S/m. The ideal material for modeling the plume would, therefore, be one with a relative permittivity of one and a conductivity adjustable within the range $0 \leq \sigma_e \leq 0.25$ S/m. The first material examined for this application was a low density plastic foam impregnated with graphite to adjust the conductivity.

The plastic foam used was a two part pourable mixture [Part A: Isocyanate (6409), Part B: Urethane Resin (R0444)] manufactured by Whitco Chemical Company, Inc. of Wilmington, DE. The foam, without any graphite added, freely expands upon mixing parts A and B to form a closed-cell structure with a density of about 2 lbs./ft.^{3} (3.24×10^{-2} gm/cm^3). The relative permittivity of the foam is $\epsilon_{er} = 1.02$. As graphite is added to the mixture (parts A and B) the conductivity of the foam increases. The addition of the graphite also causes the mixture to expand less on curing. The reduced expansion is possibly the result of the graphite acting as a heat sink, thus reducing the temperature and the expansion of the flourocarbin blowing agent, or the graphite may be causing breaks in the closed-cell structure, allowing the expanding gas to escape.

The electrical conductivity of the mixture was found not only to be a function of the percent-by-weight of graphite used, but also the density of the resulting material. For example, two samples constructed from the same weights of part A, part B, and graphite could have different conductivities if they were formed in molds with different volumes. The problem of constructing a piece of material of a given shape with a specified conductivity for use in the plume was complicated by the fact that enough of the mixture had to be placed in a mold to fill the mold when the plastic had fully cured. Since the amount of expansion of the mixture is affected by the amount of graphite present, it was difficult to determine how much material should be used in a given mold. In addition, if too much material were used, the expansion in the closed mold would increase the density of the material and, therefore, alter the electrical conductivity.

Experimental mixing curves (tables) were developed to determine the conductivity as a function of the density (after curing) for a material with a constant percentage of graphite by weight. Details of the measurement procedure are given in Appendix A. A typical curve for a material with 32% graphite by weight is shown in Figure 2. Slight variations in the density of the material for the percentage of graphite used were found to greatly affect the electrical conductivity of the samples with a high conductivity (approaching 0.25 S/m). The maximum amount of graphite that could be used in the mixture was found to be about 34%.

For samples with conductivities near the maximum required (0.25 S/m) the density was about 63 lbs./ft.^{3} (1 gm/cm^3). Materials with this density would make a plume model that is much too heavy to be suspended in the manner required for the experiments. To lower the density of the material, while maintaining the desired values of conductivity, part A of the mixture was heated. This increased the expansion slightly, but no appreciable reduction in density was obtained. In addition, a less dense foam of about 0.5 lbs/ft.^{3} (8.1×10^{-2} gm/cm^3) was tried, but this foam was found to collapse after rising.

Due to the excessive weight of the carbon loaded foam and the amount of difficulty associated with adjusting the percentage of graphite and density to obtain a desired value of the conductivity, attempts to use this material to construct the model plume were abandoned and a new material was sought.

B. Carbon Loaded Urethane Foam

Sheets of carbon loaded urethane foam are used as microwave absorbers. These are commercially available from a number of manufacturers. Unlike the

foam mixtures discussed in part A, the carbon in these sheets is <u>not</u> mixed with the catalyst or resin of the foam before curing. The impregnation with the carbon is done after the flexible foam is cured, possibly by absorption or a pressure treatment. These sheets are available with a number of different amounts of carbon loading. The effective conductivities of the sheets are not specified by the manufacturer and had to be determined from measurements made on samples of the materials. These measurements were made at a VHF frequency.

Several samples were obtained from Advanced Absorber Products, Inc. and tested to determine the range of the conductivity available. The procedure used to measure the conductivity is described in Appendix A. This company was selected because their prices per sheet were in general lower than those of their competitors and they were able to provide immediate delivery. The samples tested gave a range of conductivities $0.005 \text{ S/m} \le \sigma_e \le 0.27 \text{ S/m}$. A total of 143 sheets was purchased for use in the model plume. Each sheet had dimensions 25" x 25" x 3/8". The average density of the sheets was 5 lbs./ft.^{3} (8.1×10^{-2} gm/cm^3). The sheets are designated by an LS number which increases with decreasing conductivity. Table 1 shows the number of sheets obtained in each category and the range of conductivities measured for these sheets. Note that a circular sample was taken from the corner of each sheet and the conductivity of this sample was measured. Figure 3 shows the distribution of the measured conductivities for the sheets in each category. Here, the number of sheets in the ranges $0.25\bar{\sigma}_e \rightarrow 0.5\bar{\sigma}_e$, $0.5\bar{\sigma}_e \rightarrow 0.75\bar{\sigma}_e$, $0.75\bar{\sigma}_e \rightarrow \bar{\sigma}_e$, etc., for each category is shown as a function of the conductivity ($\bar{\sigma}_e$ is the average conductivity for the sheets in a category).

As shown in Figure 3, the conductivities for the sheets in a given category are not the same, and are distributed over a range of values with some overlap of the ranges for adjacent categories. By measuring the conductivity of each sheet, a spectrum of values was obtained that could be used to choose the appropriate material to model the computed distribution of conductivity in the exhaust plume.

III. CONSTRUCTION OF THE MODEL

Each of the sheets obtained from the manufacturer was only 3/8" thick; therefore, several of these sheets had to be rolled into a cylinder at each cross-section of the plume. The conductivities of the sheets at each cross-section were chosen to fit those predicted by the LAPP Code, cf. Figure 1. Of course, with the limited number of sheets and values of conductivity available, this fitting could only be carried out in an approximate manner. The final distribution of the material is shown in the cross-sectional drawing of the model plume in Figure 4. Each of the blocks in the drawing represents a cylinder constructed from eight layers (sheets) of foam. A total of 29 cylinders were used to construct the plume model. The average effective conductivity, σ_e, of each block (eight sheets) is shown in Table 2. The dimensions of the plume model are also shown in Figure 4. The plume model is 10' long and has a maximum diameter of 2'. The sheets and the cylindrical members of the plume were glued together using a modified neoprene contact adhesive. Photographs showing the model plume at various stages of construction are shown in Figures 5-7. After the pieces were assembled, a spent

rocket motor with the fins attached was bonded to the plume at the motor nozzle. For structural strength and to prevent moisture from being absorbed into the sheets, the plume and a small portion of the rocket were encapsulated in a layer of acrylic latex foam (JAXSAN 600 Mastic). This coating was sprayed on the outside of the plume. The average thickness of the coating was approximately 2". The total weight of the plume model with the rocket motor attached was about 98 lbs. Photographs of the finished plume model with the rocket motor attached are shown in Figures 8 and 9.

The effective conductivity of the plume model as a function of position is shown in Figure 10. This is to be compared with the conductivity obtained from the LAPP code in Figure 1.

IV. PRELIMINARY TESTS

The missile with the model plume was placed in an anechoic chamber at the Naval Surface Weapons Center/Dahlgren, VA and exposed to electromagnetic waves at a variable angle of incidence θ_i, (θ_i is the angle formed by the propagation vector, $\vec{k}$, and the axis of the missile, see Figure 11). The incident electric field was vertically polarized, i.e., the electric field vector $\vec{E}$, was in the plane formed by the propagation vector and the axis of the missile. The coupling to the interior of the missile was measured by monitoring the voltage at a test point in the circuitry in the interior of the missile. Very few modifications were made on the missile so as to minimize any deviation from an actual missile in flight. Only preliminary measurements have been made to date with this model, and some of the data from these are

included here mainly to show the qualitative agreement between the measurements with the model plume and an appropriate theory.

Measured results for the missile alone and the missile with a plume are shown in Figure 12. These graphs show the measured patterns for the voltage received at the interior test point (in dB) corrected for any deviation from a square-law response. For this example, the length and radius of the missile are $\ell_m = 0.89\lambda$ and $a = 0.029\lambda$.

For the missile being considered, the principle aperture for coupling of the electromagnetic energy to the interior is located near the nose of the missile and is nearly rotationally symmetric about the axis of the missile. A theoretical analysis of the missile with an exhaust plume was performed using a theory which approximates the missile and the plume by a thin wire structure; the details of this are given in reference [2]. In Figure 13, theoretical patterns are shown for the normalized time-average power, p_n, transmitted through a small aperture near the nose of the missile. Results are shown for the missile without a plume, for the missile with a plume that has an approximation to the distribution of conductivity shown in Figure 1, and for the missile with a plume having an approximation to the distribution of conductivity corresponding to the model plume shown in Figure 10. Due to the discrete nature of the segments that form the model plume, the theoretical patterns computed using it (dashed line in Figure 13b) and the plume in Figure 1 (solid line in Figure 13b) are different.

A qualitative comparison of the patterns for the missile without a plume (Figures 12a and 13a) shows close agreement between the measured data and the theoretical results computed for an aperture near the nose of the missile.

When the plume is added, the theoretical pattern for the LAPP plume is also in good qualitative agreement with the measured pattern. The measured pattern, however, has a definite ripple superposed on it. When a theoretical model for the plume composed of discrete segments with different internal impedances, like the experimental model, is used in the analysis, the ripple is also present in the theoretical results (dashed line in Figure 13b). The exact amplitude of the ripples and their location are not reproduced in the theory, since the full complexity of the model plume cannot be included in the simple theoretical analysis. The ripples in the experimental pattern are, therefore, considered an anomaly introduced by the modeling procedure.

Both the experimental and the theoretical data indicate that at this frequency the presence of the exhaust plume has only a small effect on the coupling through the aperture near the nose. The presence of the plume causes a slight decrease in the size of the lobes in both the experimental and the theoretical patterns.

V. CONCLUSION

A full-scale model of the exhaust plume for a specific missile has been constructed. The knowledge of the materials used and the procedures for fabrication of this model will be useful in constructing models for the exhaust plumes of other missiles.

Future tests will be conducted to determine the accuracy of this modeling procedure. Specifically, in these tests, results such as the pattern shown in Figure 12, will be measured for the missile with the actual exhaust plume and the missile with the model of the plume. Since the model was constructed

using results computed from the thermo-chemical analysis (LAPP code) this comparison will also indicate whether the computer code can be used to select the electrical constitutive parameters for the model or if measurements of the electrical constitutive parameters made on the actual plume are required.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. S. Bray, Mr. R. Williams, and Mr. J. Cockey of NSWC/Dahlgren, VA, for performing the pattern measurements in their anechoic chamber and Dr. W. Walker at MIRADCOM/Huntsville, Alabama, for assisting with the LAPP Code Analysis.

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[1] J. D. Nordgard and G. S. Smith, "Plasma Model of Missile Exhaust Plumes," Tech. Report RADC-TR-77-144, Rome Air Development Center, April 1977. (A040057)

[2] G. S. Smith, J. D. Nordgard and J. Edwards, "The Alteration of the Surface Current on a Missile by the Presence of an Exhaust Plume," IEEE Trans. EMC, 19-30, November 1977.

APPENDIX A

Measurement of Material Parameters

Measurements of the relative effective permittivity, ε_{er}, and effective conductivity, σ_e, were made on the carbon loaded samples using a GR-1690-A dielectric sample holder and a GR-1602-B admittance meter. These measurements were made at a VHF frequency on circular disks of the foam which were roughly 1" in diameter and 0.1" in thickness. Metal foil was applied to each circular face of the sample so that the sample would make good electrical contact with the holder. A block diagram of the measurement setup is shown in Figure A1 and a photograph appears in Figure A2.

The procedures for high-frequency measurement as described in the General Radio Instruction Manual were followed.*

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*General Radio, "Instruction Manual for Type 1690-A Dielectric Sample Holder," 1968.

Type	Number Ordered	Measured Range of Conductivities (S/m)
LS–100	20	0.986–0.269
LS–200	12	0.0548–0.120
LS–500	36	0.0249–0.0816
LS–1000	41	0.0185–0.0654
LS–10000	34	0.00493–0.0196

Table I

Measured Range of Conductivities of Various Types of Carbon Loaded Urethane Foam Sheets.

$\bar{\sigma}_e$ (S/m)

Section	Layer			
	a	b	c	d
1	0.255	N/A	N/A	N/A
2	0.206	0.0549	N/A	N/A
3	0.193	0.141	0.0419	N/A
4	0.0987	0.180	0.0328	0.0142
5	0.0488	0.156	0.0421	0.00104
6	0.0189	0.110	0.0698	N/A
7	0.00935	0.0783	0.0688	N/A
8	0.00905	0.0665	0.0606	N/A
9	0.00882	0.0381	0.0528	N/A
10	0.00832	0.0244	0.0293	N/A

Table II

Average Values of the Effective Conductivities of the Materials Used in the Various Sections and Layers of the Plume Simulator.

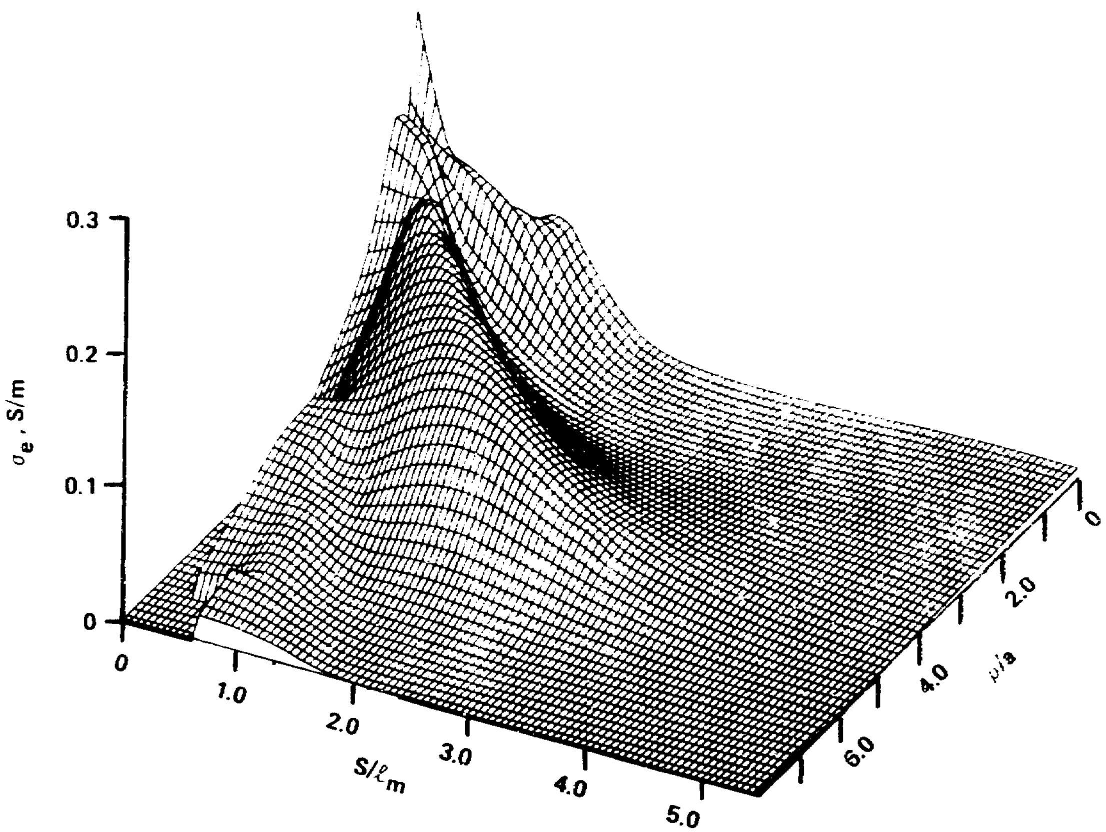


FIGURE 1 EFFECTIVE CONDUCTIVITY σ_e OF MISSILE EXHAUST PLUME AS A FUNCTION OF NORMALIZED AXIAL AND RADIAL POSITIONS, S/ℓ_m AND ρ/a, AS COMPUTED FROM THERMOCHEMICAL ANALYSIS. NOTE THAT THE SCALE FOR THE RADIAL AXIS (ρ/a) IS EXPANDED BY ABOUT A FACTOR OF 12.

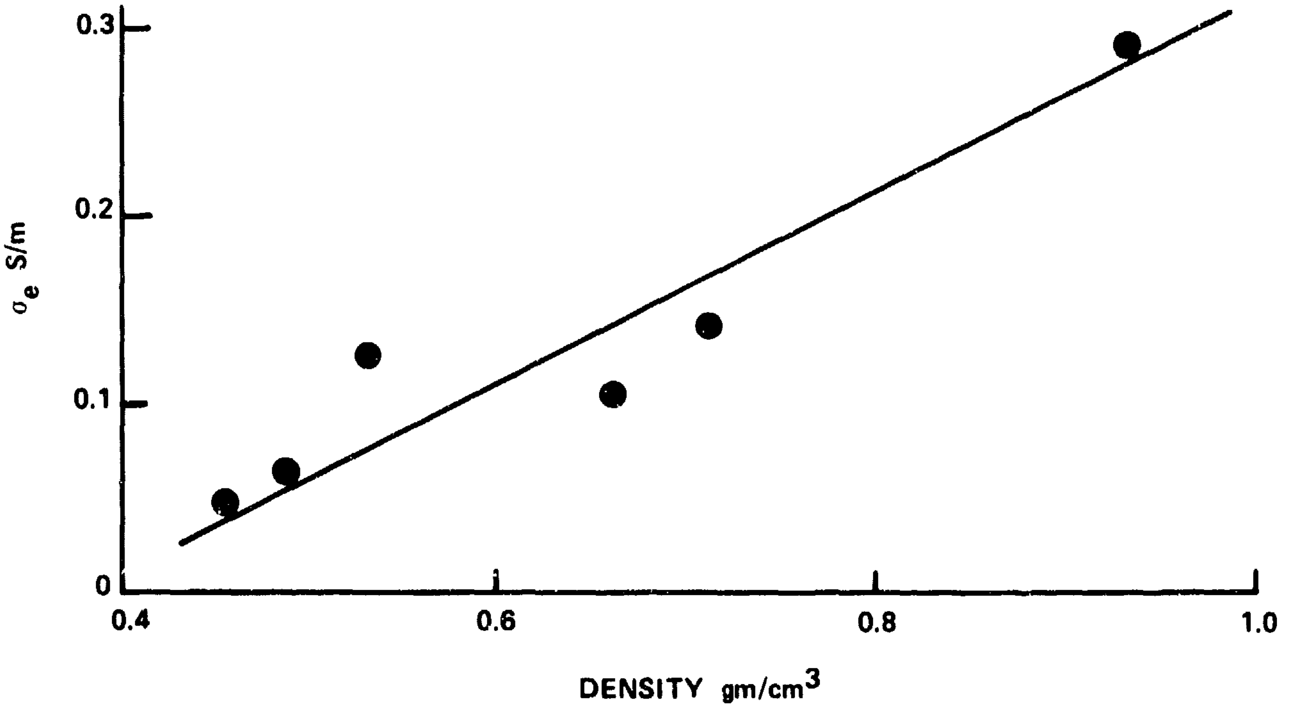


FIG. 2 EFFECTIVE CONDUCTIVITY AS A FUNCTION OF THE DENSITY FOR A MIXTURE WITH 32% BY WEIGHT OF GRAPHITE.

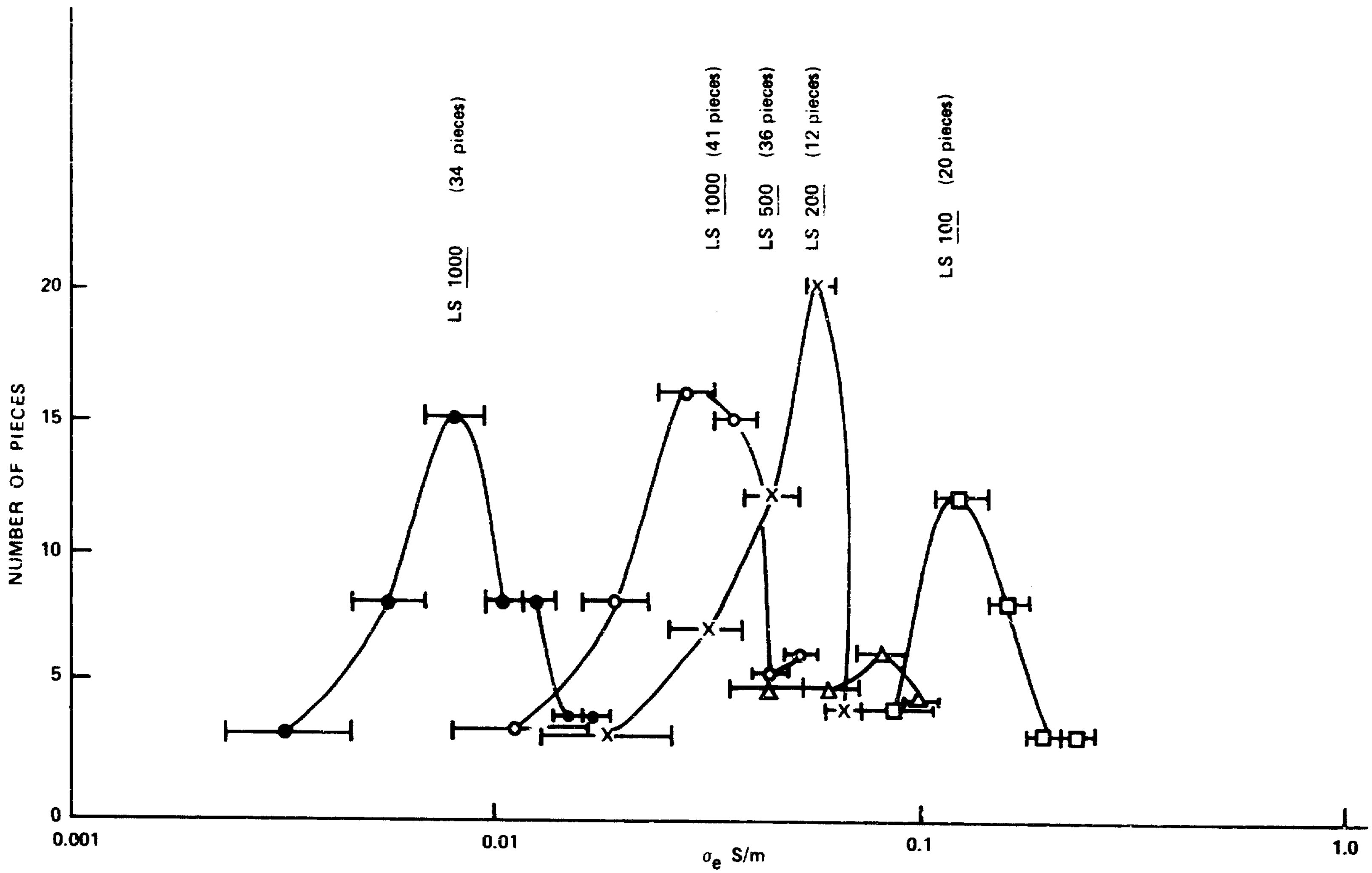


FIG. 3 THE DISTRIBUTION OF CONDUCTIVITIES FOR THE SHEETS TESTED AT VHF FREQUENCY.

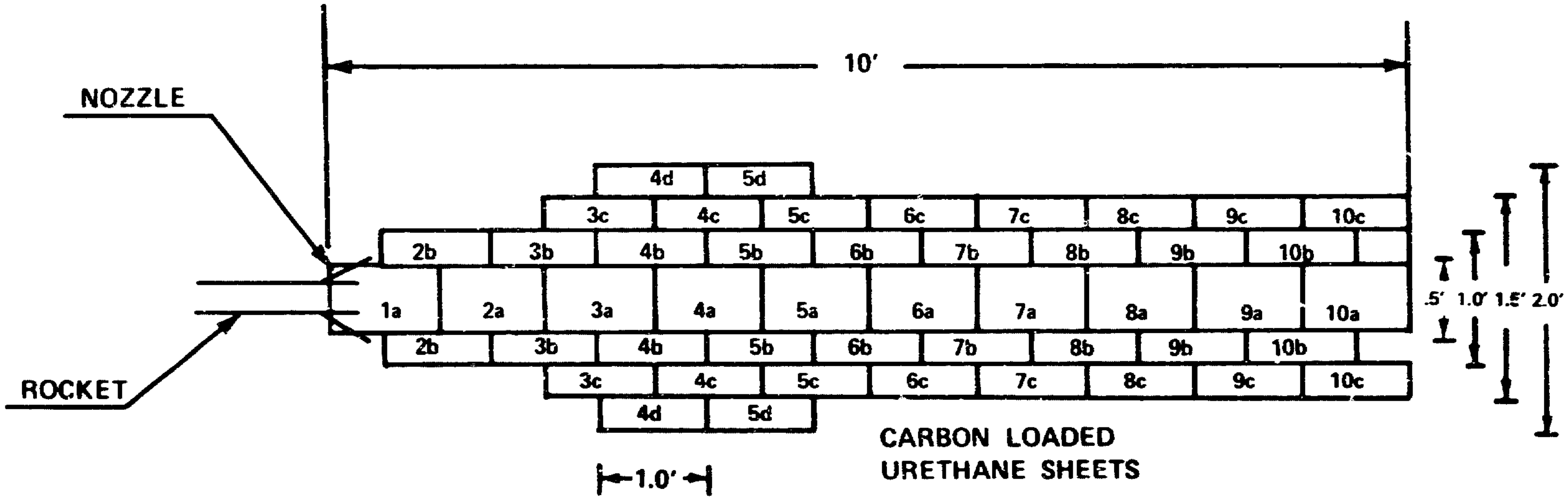


FIG. 4. CONSTRUCTION DETAILS OF THE PLUME SIMULATOR.

FIGURE 5. DETAIL OF CONSTRUCTION OF PLUME SIMULATOR.

FIGURE 6. DETAIL OF CONSTRUCTION OF PLUME SIMULATOR.

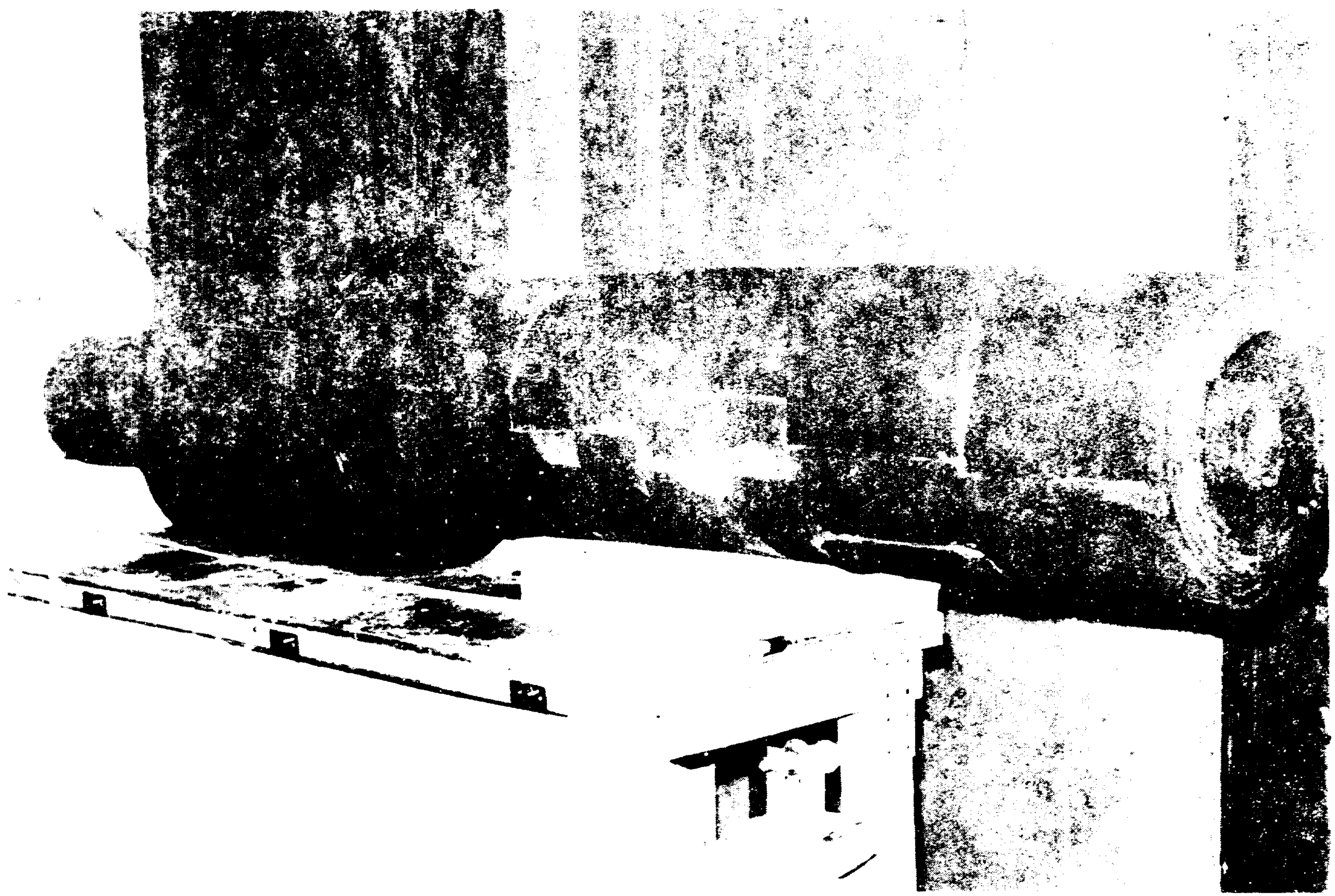


FIGURE 7. DETAIL OF CONSTRUCTION OF PLUME SIMULATOR.

FIGURE 8. COMPLETED PLUME SIMULATOR WITH ROCKET MOTOR ATTACHED.

FIGURE 9. DETAIL OF ATTACHMENT OF PLUME SIMULATOR TO ROCKET MOTOR.

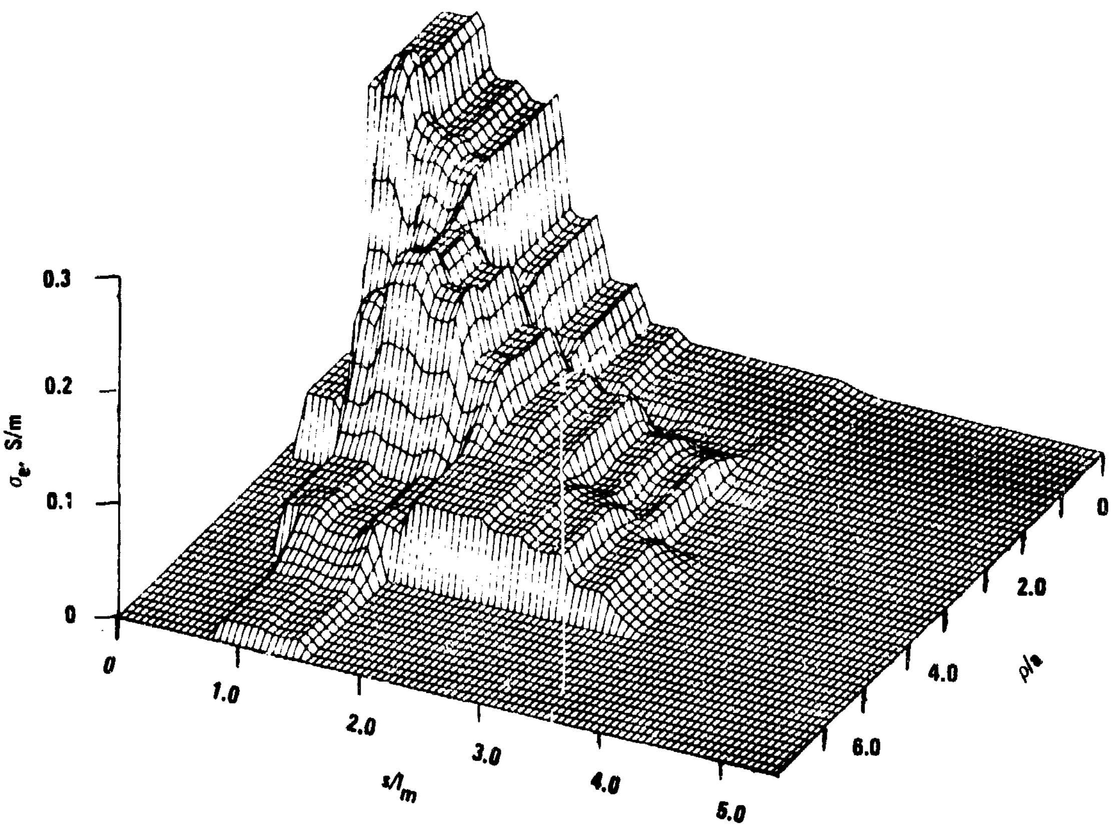


FIG. 10. CONDUCTIVITY OF SIMULATED EXHAUST PLUME. NOTE THAT THE SCALE FOR THE RADIAL AXIS (ρ/a) IS EXPANDED BY ABOUT A FACTOR OF 12.

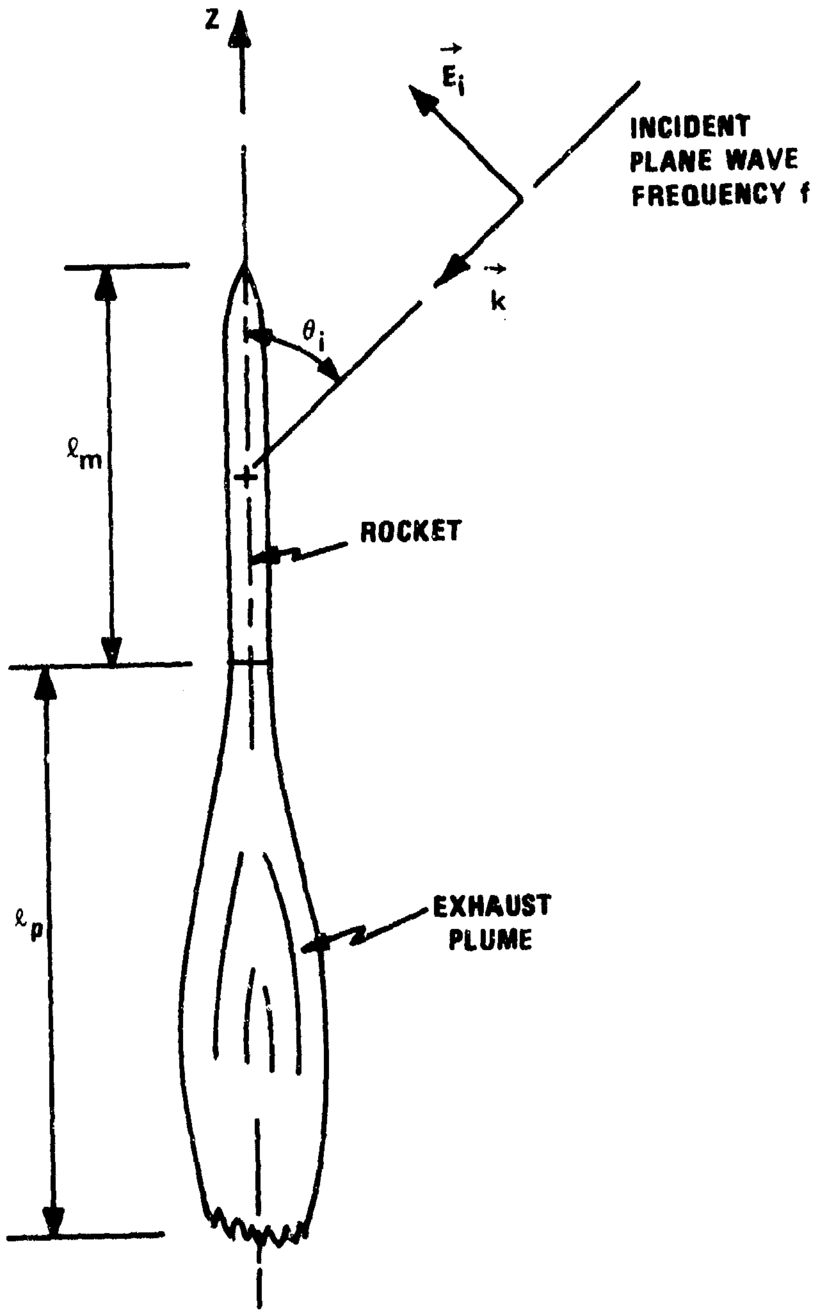


FIGURE 11. IDEAL EXPOSURE GEOMETRY.

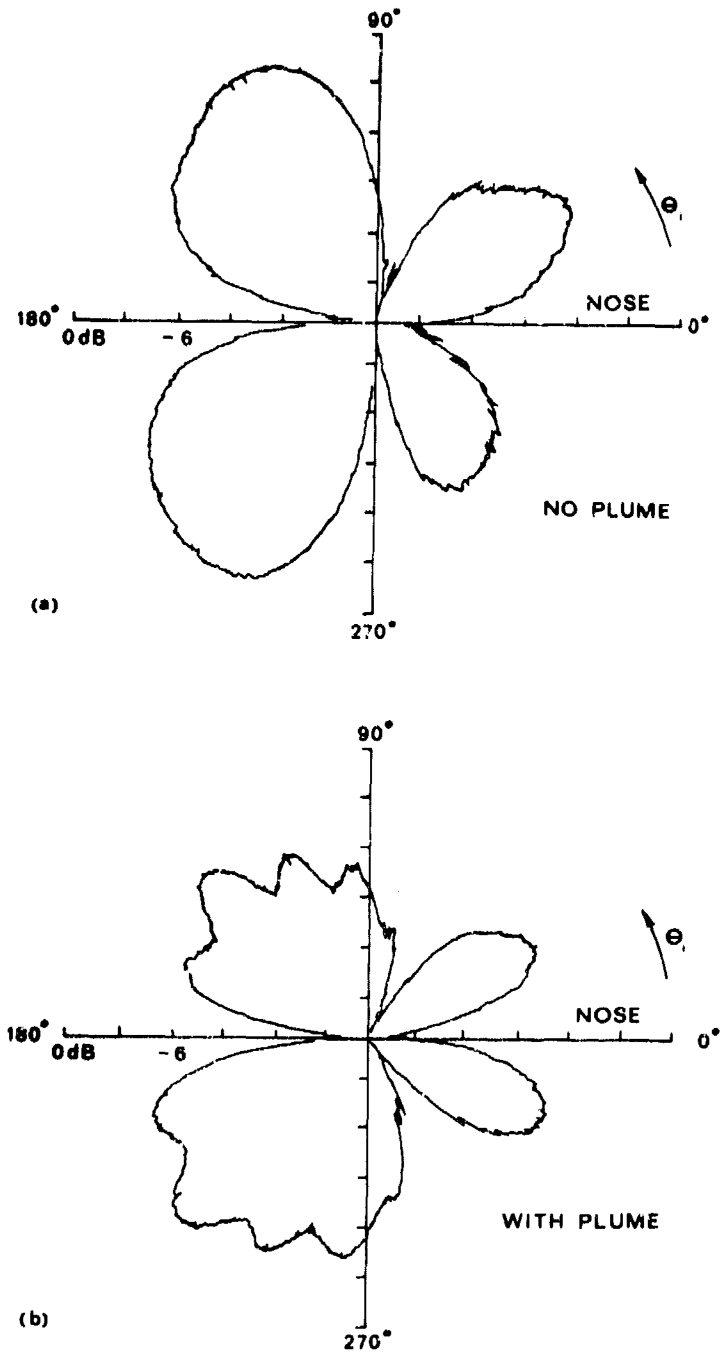
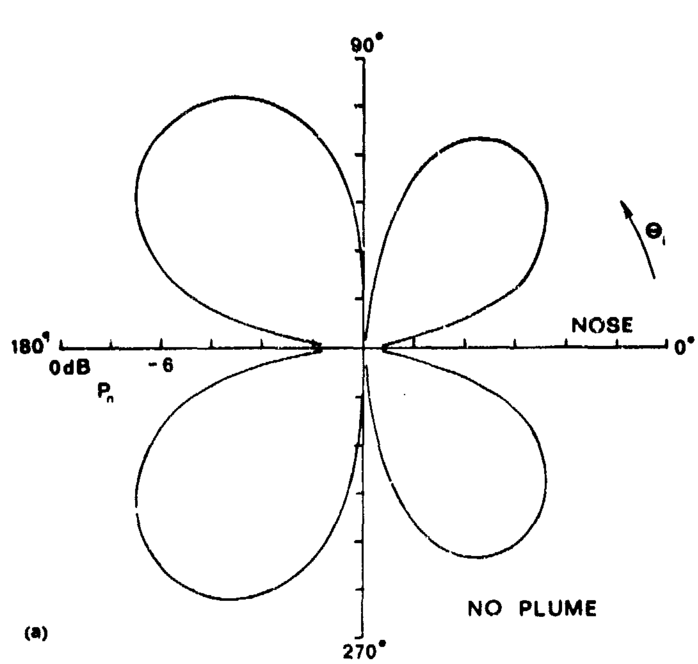


FIG. 12. EXPERIMENTAL PATTERNS FOR VOLTAGE MEASURED AT INTERNAL TEST POINT, (a) MISSILE WITHOUT PLUME, (b) MISSILE WITH PLUME, $\ell_m/\lambda = 0.89$, $a/\lambda = 0.029$.



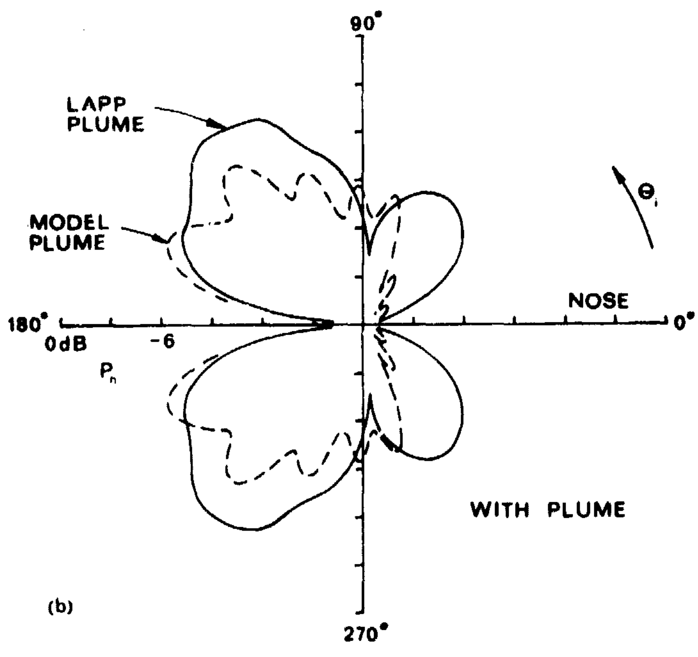


FIGURE 13. THEORETICAL PATTERNS FOR NORMALIZED TIME–AVERAGE POWER TRANSMITTED THROUGH AN APERTURE NEAR NOSE OF MISSILE, (a) MISSILE WITHOUT PLUME, (b) MISSILE WITH LAPP PLUME (SOLID LINE) AND WITH MODEL PLUME (DASHED LINE), ℓ_m/λ = 0.89, a/λ = 0.029.

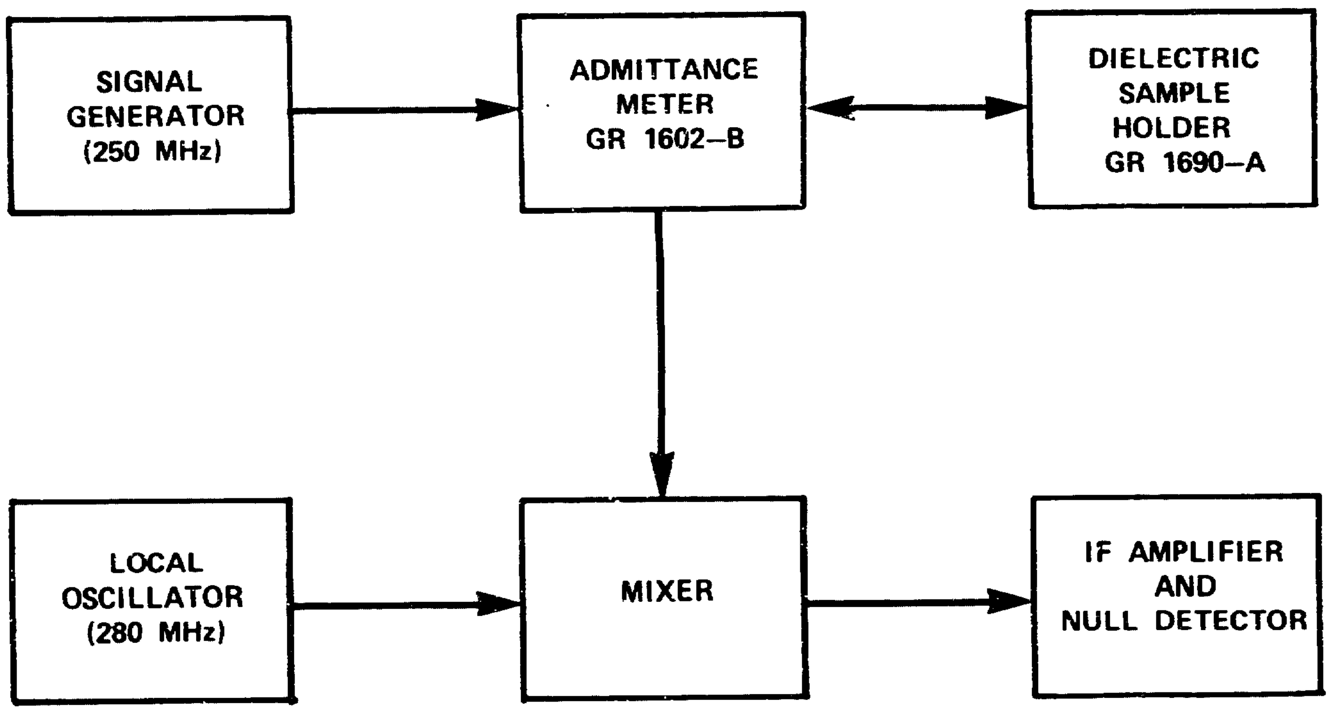


FIG. A1 BLOCK DIAGRAM OF MEASUREMENT SETUP FOR DETERMINING ELECTRICAL PROPERTIES OF MATERIALS.

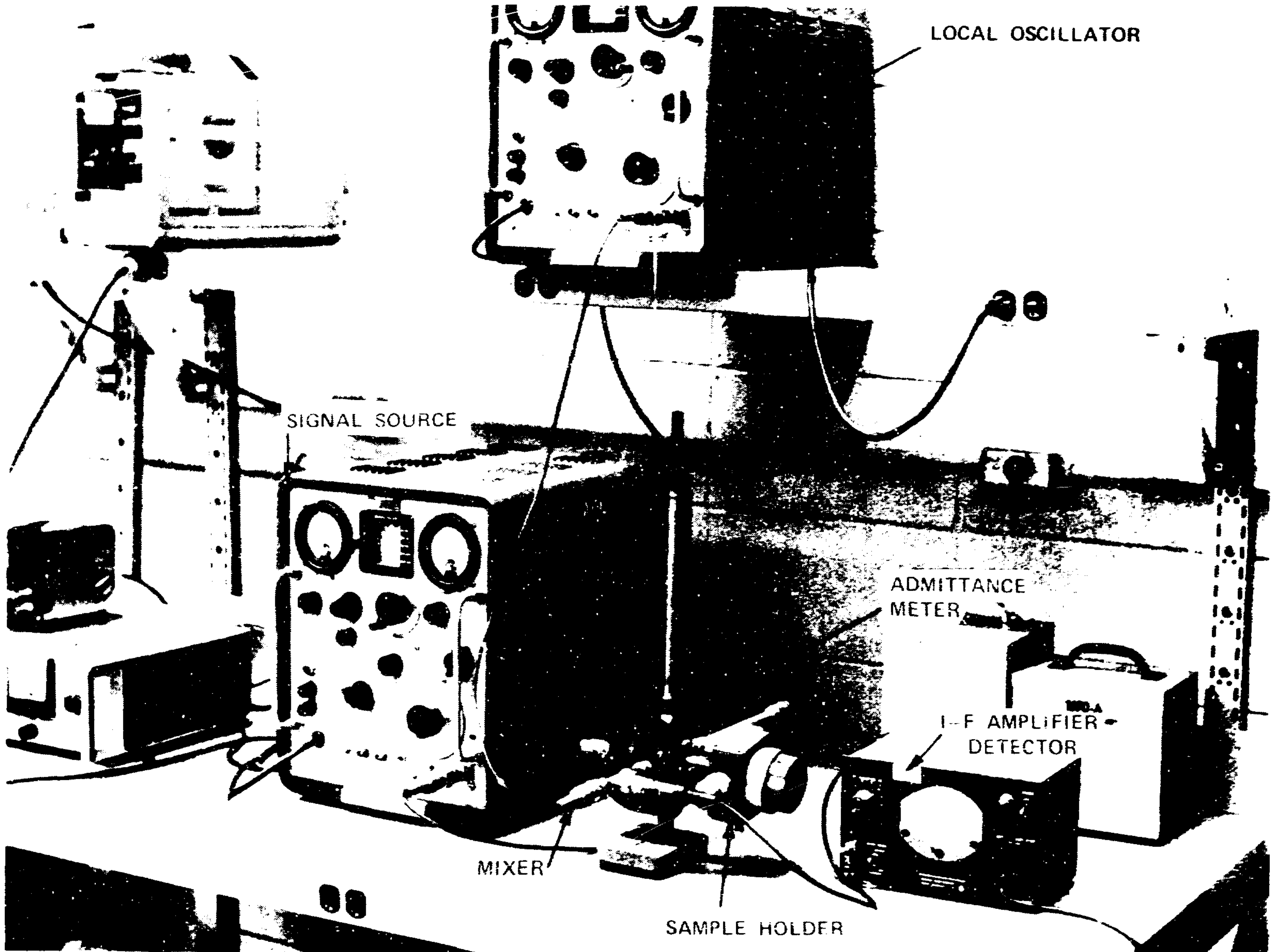


FIGURE A2 MEASUREMENT SYSTEM FOR DETERMINING THE ELECTRICAL PROPERTIES OF SAMPLES OF MATERIAL.

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